VeeR: Exploring the Feasibility of Deliberately Designing VR Motion that Diverges from Mundane, Everyday Physical Motion to Create More Entertaining VR Experiences

ANONYMOUS AUTHOR(S)

Fig. 1. This work explores the feasibility of using veering techniques to turn mundane, everyday motion, such as (A) a straight-line movement of a metro train between 2 metro stations, into (B) a more entertaining VR motion experience. This metro route (A) is one of the actual routes used in our two studies with a combined total of 42 participants, with the VR motion design (B) being based on actual results of users' most preferred rate and direction of veering for accelerating, cruising, and decelerating phases.

This paper explores the feasibility of deliberately designing VR motion that diverges from users' physical movements to turn mundane, everyday transportation motion (e.g., metros, trains, and cars) into more entertaining VR motion experiences, in contrast to prior car-based VR approaches that synchronize VR motion to physical car movement exactly. To gain insight into users' preferences for *veering rate* and *veering direction* for turning (left/right) and pitching (up/down) during the three phases of acceleration (*accelerating*, *cruising*, and *decelerating*), we conducted a formative, perceptual study (n=24) followed by a VR experience evaluation (n=18), all conducted on metro trains moving in a mundane, straight-line motion. Results showed that participants preferred relatively high veering rates, and preferred pitching upward during acceleration and downward during deceleration. Furthermore, while veering decreased comfort as expected, it significantly enhanced immersion ($p<.01$) and entertainment ($p<.001$) and the overall experience, with comfort being considered, was preferred by 89% of participants.

CCS Concepts: • **Human-centered computing** → **Walkthrough evaluations**; **User interface design**.

Additional Key Words and Phrases: User Experience Design, Virtual Reality, Opportunistic Haptic, Motion Sensation

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1 INTRODUCTION

Transportation is the intentional movement from one location to another, and transportation routes, such as public transit and freeways, are deliberately designed to be relatively straight with gradual turns for comfort and safety. For example, the veering rates for metros and cars are generally below 4.5 $^{\circ}/sec$ [3] and 15.0 $^{\circ}/sec$ [48] [37], respectively, in contrast to roller coaster rides with veering rates of 90 $^{\circ}/sec$ and higher [13], as shown in Figure 2(b).

This paper investigates the feasibility of deliberately designing VR motion that diverges from users' physical movements, with the aim of transforming mundane, everyday motions into more entertaining experiences, as shown in Figure 2(a). In contrast to previous in-car VR approaches that mirror VR motion exactly to the physical car movement, our veering approach explicitly designs VR motion that deviates from users' physical motion. Furthermore, compared to motion platforms that aim to generate physical motion to match VR motion, we explore the feasibility of using veering for existing, everyday motion.

While veering has the potential to provide designers with increased flexibility to enhance the immersion and entertainment of VR motion experiences, deviation from physical motion introduces sensory conflict [24] that could cause discomfort. The open research question this work aims to answer is whether veering can enhance the overall experience with comfort taken into account.

We structured this research into two parts, each with an in-situ user study: 1) a formative, perceptual study to understand users' preferences for veering while in motion, and 2) an user experience evaluation of diverged VR motion experiences based on these veering preferences.

The formative study is needed because prior studies that have diverged VR vs. physical motion focused on *detection thresholds* (lower-bound) and *acceptable thresholds* (upper-bound) for redirecting users' physical heading [35] [38] [5], while we are interested in users' *preferred veering rate* and *preferred veering direction* for diverging users' motion in VR without changes to users' physical motion.

We conducted a formative perceptual study with 24 participants on metro trains moving in a straight line to understand user-preferred veering during mundane, everyday motion. Results showed that participants most preferred a veering rate of 60~ 80 $^{\circ}/sec$ for left/right (yaw) and up/down (pitch) directions. Interestingly, this high range of preferred veering rate is close to the veering rate of theme park roller coaster designs [13], showcasing the potential for substantial flexibility in VR motion path designs during mundane, everyday motion. In terms of veering direction, participants most preferred pitching up during acceleration and pitching down during deceleration.

Based on these veering preferences, we designed motion paths for two VR scenes. We then conducted a summative user experience evaluation study for VR motion experiences on moving metros to compare veering in VR during physical motion with two baselines: 1) with vs. without veering while experiencing physical motion; and 2) veering with vs. without physical motion. Results from the 18-person study showed that veering significantly improved immersion($p < 0.01$) and entertainment level ($p < 0.001$) with large effect sizes($r > 0.5$) vs. the baseline without veering. Although comfort decreased as expected due to sensory conflict [24], the overall experience, with comfort being taken into consideration, showed that veering was preferred by 89% of participants. Moreover, when compared to veering while being stationary, the mundane, everyday motion significantly improved immersion, realism, and entertainment ($p < 0.001$) with large effect sizes ($r > 0.5$). Perhaps unsurprisingly, 100% of users preferred the experience with physical motion vs. without.

In summary, our key contributions are as follows:

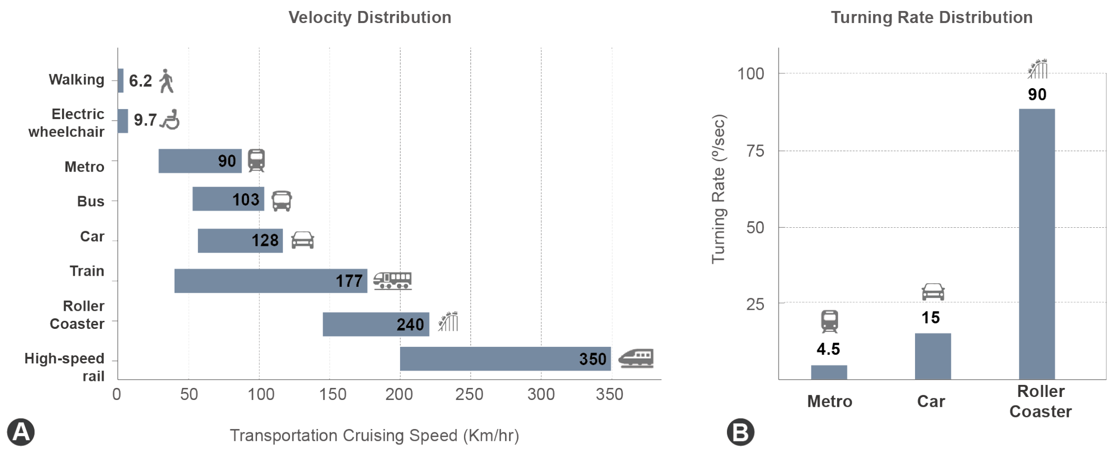

Fig. 2. (A) Ranges of linear cruising speeds for various kinds of real-world transportation, where those with higher speeds have yet to be investigated for VR veering. (B) Ranges of veering rates in everyday use of different vehicles, showing the relative mundanity of travel by metro and car.

(1) Understanding of users' most-preferred veering rate and veering direction for VR motion experiences during mundane, everyday motion.
(2) Applying veering to VR motion design significantly improves immersion, entertainment, and with comfort being taken into consideration, the overall user experience.
(3) Demonstration of the opportunity to design VR motion experiences similar to theme park roller coaster rides even when users are physically experiencing mundane, everyday motion, through two in-situ studies with a combined total of 42 participants.

2 RELATED WORK

2.1 Redirecting Physical Paths in VR

Redirected walking is a VR technique that aims to enable users to walk in a physically limited space while experiencing the illusion of walking in a much larger virtual environment by influencing the physical heading and walking path taken by users. Techniques include interactively and imperceptibly rotating the virtual scene about the user [35]. Alternatively, Matsumoto et al. [27, 28] proposed the use of additional haptic cues (e.g., a physical wall for users to touch) and found that they could reduce the amount of perceived curvature in real-world path. Suma et al. [46] focused on the dynamic planning and optimization of the original visual rotation technique to adapt to different users and VEs. The scope of this redirected walking technique has also been expanded to be applied to different rotation axes including pitch [29] and roll [50], as well as specific behaviors such as opening doors [19].

Studies have identified the detection thresholds of such rotational deviation and awareness, as influenced by factors including field of view, gender, distractors [49] and the curvature of virtual paths [25] and have identified detection thresholds of 7-28 $^\circ/sec$ for walking [6] and 4.5 $^\circ/sec$ for wheelchairs [7]. Schmitz et al. [41] further proposed the use of immersion to determine appropriate rotational gains.

In addition to the rotation gains used in redirected walking, researchers have also instrumented techniques to induce changes in users' walking pace. Ishikawa et al. [20] achieved this through the visual alteration of pitch in the VE, whereas Abtahi et al. [1] identified increasing the virtual avatar's size also increased real-world walking speed. Grechkin et al. [15] found that these translational gains were independent from redirected walking's curvature gains.

While redirected walking and wheelchairs aim to affect the physical heading and path taken by users, our veering approach diverges the virtual motion path without changes to the physical motion path.

2.2 In-car VR Experience

Extensive research has explored in-car VR experiences by generating VR motion that matches real-world car motion exactly 1:1 to improve comfort and immersion. For example, holoride [18] for cars creates moving backgrounds, based on the physical movement, to enhance the experience of 2D movies and games. For more immersive experiences, rail shooter [44] is a type of action-based video game in which player control is limited to directing where to fire a virtual gun or move their avatar around the screen, without controlling the path their avatar takes. Examples include CarVR by Hock et al. [17] that mapped a car's real-world motion on the road to a helicopter in VR, and holoride's [18] mapping to airplanes, flying superheros, and spaceships. Researchers have also considered using VR to convert the landscape outside the vehicle into imaginary settings for mindfulness [34] and escapism [16]. To mirror the car's movements for these purposes, Haeling et al. [16] made use of 6-DoF head-tracking while McGill et al. [32] presented PassengXR, an open-source software toolkit to create extended reality experiences based on the vehicle telemetry obtained from a reference set of hardware.

One commonly-investigated concern with in-vehicle VR experiences is user comfort. As a result, researchers have explored means of mitigating VR sickness. For example, Cho and Kim [9] validated the approach of dynamically distorting the pathways in the VE in order to emulate actual optical flow and significantly reduce the sickness level. McGill et al. [31] concluded that in seeking the balance between user immersion and comfort, different solutions are required to cater to the preference and susceptibility to sickess of different users. Similar work has also been extended to other modes of transport, such as in Matviienko et al.'s [30] investigation of the effects of steering methods and trajectory for bicycles, as well as Soyka et al.'s [43] experiments on VR sickness with turbulent motions within airplanes. Beyond VR sickness, Li et al. [26] also identified the means to preserve VR immersion while ensuring awareness of real-world location and conditions.

Our veering approach differs in that we explore the feasibility of deliberately diverging VR motion from the physical motion, to understand its effect on user experience during mundane, everyday motion.

3 FORMATIVE, VEERING PREFERENCE USER STUDY

We conducted a formative, perceptual study to understand participants' preferences for veering during mundane, everyday transportation motion, which inherently has three acceleration phases: *accelerating*, *cruising*, *decelerating*. Specifically, we collect the most-preferred veering rate and veering directions across these three acceleration phases.

As designing and conducting VR experiments while experiencing physical motion is significantly more challenging than in-lab studies, we conducted three 8-person pilot studies to inform various aspects and parameters of the study design to cap the experiment duration to one hour, to reduce burden on participants and maintain feedback quality.

3.1 Study Design

This study used a within-subjects design with a single independent variable: the physical acceleration phase, and two dependent variables: most-preferred veering rate and veering directions. Additionally, we collected VR sickness assessment and qualitative feedback through semi-structured interviews.

Fig. 3. Overview of the metro train and route used for the two user studies: (a) a satellite view of the straight-line section of a popular above-ground metro train route, showing the five stations (A-E) with similar distances between stations; (a) Study participants stood comfortably facing the metro's forward direction and held on to a pole for stability, while being accompanied by two experimenters for safety (not shown).

3.1.1 Physical Motion. For the choice of mundane, everyday physical motion suitable for repeating experiments, we identified a straight-line section of a popular above-ground metro train route[1]. The metro train is fully automated, which provided consistent durations for the three acceleration phases. The chose section, shown in Figure 3(a), consists of 5 stations with 4 inter-station segments with similar distance and acceleration phases: 15-20 seconds of accelerating, 30-50 seconds of steady cruising at up to 60km/hr, and 15-20 seconds of decelerating, for a total duration of 70-80 seconds.

3.1.2 Safety and VR Sickness. Participants were accompanied by two experimenters at all times, one of whom's sole responsibility was ensuring participant safety. While on the metro, participants stood comfortably facing the metro's forward direction. When wearing VR headsets and also while train is in motion, participants held on to a pole for stability and safety, as shown in Figure 3(b). The experiments were conducted during non-peak hours to ensure ample space around the participants.

To safeguard against discomfort and VR sickness, participants could terminate the experiments at any time at will, and extend the resting periods for as long as needed. Additionally, we collected user-reported VR sickness assessment 3 times throughout the study, using a 10-point Fast Motion Sickness Scale (FMS), which multiple prior studies have used [36] and have been shown to be reliable and highly correlated (rho=0.785-0.84) [2, 23] with the full, 16-question Simulator Sickness Questionnaire (SSQ) [40]. On the 10-point scale, 1 indicated no sickness at all, and 10 indicated severe sickness that would terminate the experiment.

3.1.3 Veering Directions. The three axis for veering are yaw (left/right), pitch (up/down), and roll (clockwise/counter-clockwise). Yaw and pitch are the most common in everyday transportation, while roll easily induces VR sickness, therefore we focus on yaw and pitch for this paper.

For pitch, the vestibular detection threshold is asymmetrical for up vs. down, while symmetrical for left vs. right [42] [47]. We conducted a 8-person pilot study on the metro for veering left/right and up/down in VR across the three acceleration phases, in counter-balanced ordering. Participants reported that the veering experience was similar

[1]City, metro, route, and station names anonymized for review.

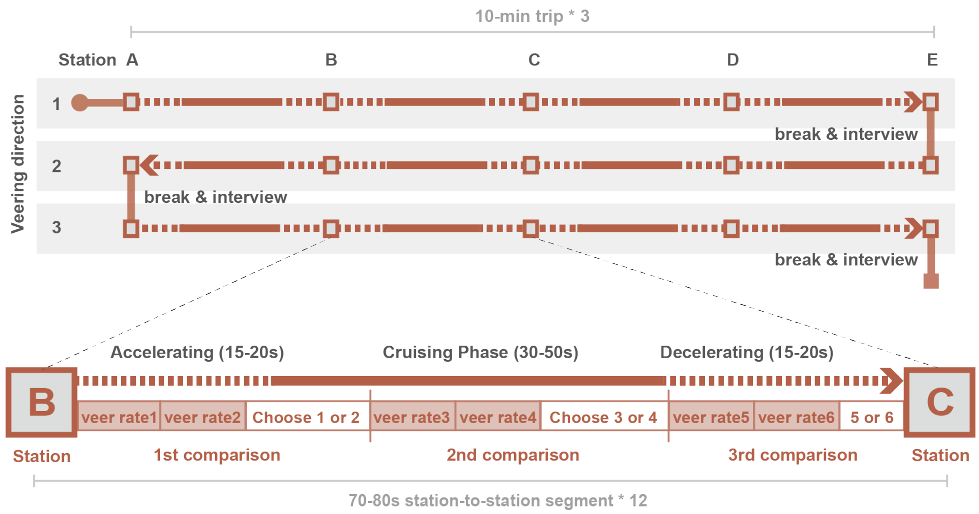

Fig. 4. Experimental procedure consists of three trips with different veering directions. Each trip comprises four inter-station segments, with five stations labeled as Station A through E. There is an 8-minute break and a brief semi-structured interview after each trip. Each inter-station segment consists of three acceleration phases: accelerating, cruising, and decelerating. During each phase, two veering rates are compared, and one of them is selected by participant.

for left vs. right, but highly distinct for up vs. down. Therefore, we merged the left/right conditions, resulting in a total of 3 conditions: 1) TURNING LEFT/RIGHT (YAW), 2) PITCHING UP, and 3) PITCHING DOWN.

3.1.4 Veering Rate. As the initial step to explore the feasibility of veering, the goal for this formative study is to identify the most-preferred rates with sufficient accuracy to serve as a general model (i.e. same rates for all users) for the summative user experience evaluation. Unbounded approaches, that let participants freely adjust for unlimited number of times, are not applicable when there is a fixed number of route segments and when controlling for exposure to potential VR sickness.

In order to further control for VR and motion exposure to the same duration, we used a fixed-height, decision tree method (i.e. binary search), adapted from the adaptive method of limits for differential thresholds from *Application of Psychophysical Techniques to Haptic Research* [21], which used a fixed number of decisions to arrive at a value range with acceptable resolution.

The decision tree works as follows:

(1) A pair of two veering directions, *low* vs. *high* in randomized ordering, of the same veering type are presented consecutively during the same acceleration phase, and the participant chooses whether the first or the second experience was preferred.
(2) If *low* is preferred, then *high* will be lowered to $(low + high)/2$, whereas if *high* was preferred, then *low* will be raised to $(low + high)/2$.
(3) Repeat Step 1 & 2 for the height of the decision tree.

To identify a suitable upper and lower bounds of rates for the decision tree, we conducted a second 8-person pilot study, and set the initial (low = 5, $high$ = 245), which corresponds to a resolution of 15° after 4 decisions. Across all

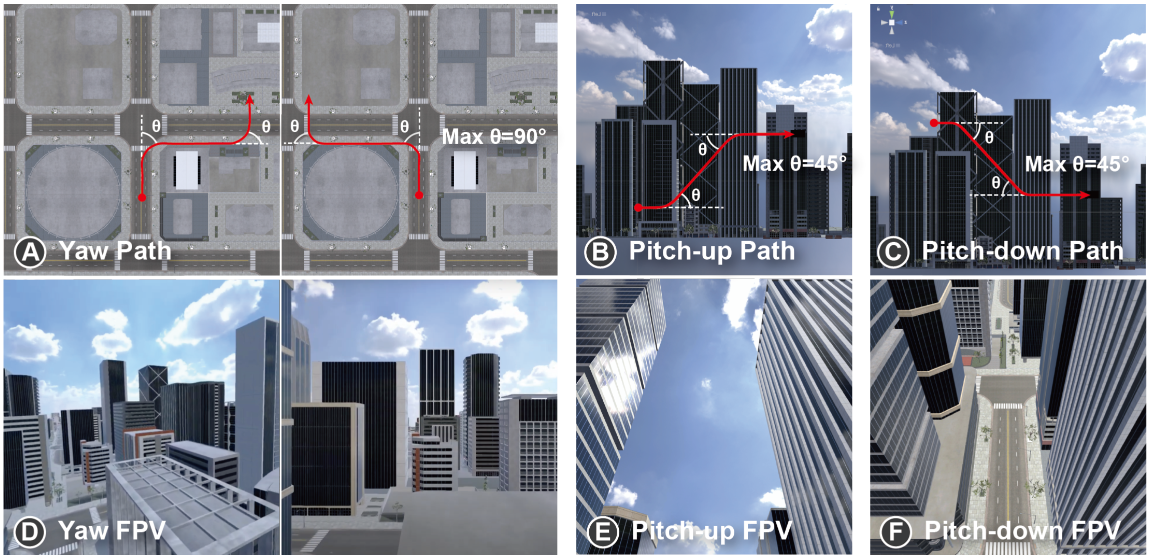

Fig. 5. The VR scenes and paths participants experienced for the formative study: (A) Veering left/right: each path consists of two alternating turns: left-right and right-left, with a maximum turning angle of 90 degrees, (B) side view of a downward pitch followed by an upward pitch, and (C) side view of an upward pitch followed by a downward pitch. (D), (E), and (F) are their respective first-person views.

three acceleration phases, the resulting veering rate ranged from $10°/sec$ to $220°/sec$ (median=$100°/sec$). Therefore, we set the decision tree to have initial [$low = 5$, $high = 245$], with a height of 4 that corresponds to the 4 station-to-station segments in a one-way trip, producing a final rate range resolution of $15°/sec$.

Overall, each participants completed 4 rate comparisons for each of the three veering directions for each of the three acceleration phases for a total of 36 veering rate comparisons: 4 comparisons x 3 acceleration phases x 3 veering directions. The order of veering directions was counterbalanced.

3.1.5 Veering Paths in VR 360. We developed a VR 360 city environment and study software using Unity (version 2022.3.4f1), with motion paths for each veering direction, as shown in Figure 5. The angles of the turns for yaw and pitch are 90 and 45 degrees, respectively, based on the most popular turning angle of first-person view (FPV) video paths surveyed by TurnAhead [22]. Each yaw path consists of two turns of a maximum of 90 degrees in alternating directions, to return the original heading, as shown in Figure 5(A). Each pitch path consists of one up/down rotation, followed by a corresponding down/up rotation to return to the original pitch, as shown in Figure 5(B)(C).

The forward speed of all the VR motion experiences in this study is constant, and matched to the 60 Km/hr of the metro's cruising speed, rather than the exact speed of the metro. This simplification was made based on pilot study feedback, as the study was already long at more than 1 hour. By controlling for VR speed, we were able to eliminate it as an experimental factor to avoid adding 40 minutes to the study duration which would become nearly 2 hours with risks of reduced user data quality. Furthermore, our summative study was designed to have VR speed be based on the physical speed, which would provide an opportunity to validate and collect feedback on these preferences.

3.2 Study Procedure

We met with participants at Metro Station A, where we introduced the study procedures and informed them that they could pause or stop the experiment at any time at will. We also asked them to complete a consent form, demographics survey, and the Motion Sickness Susceptibility Questionnaire (MSSQ) [14], which helps gauge population sampling and also the applicability of our results to individuals with varying degrees of motion-sickness sensitivity. At the station, participants practiced using the Quest 2 VR headset and one comparison of two random veering rates to become familiar with the procedures and scenarios.

Next, we asked participants to remove their HMDs and follow the experimenters to board the metro train. While the metro train is in the station, we allocated a safe standing spot within the metro carriage, where handles were available and without obstructing the movement of other passengers. Participants were instructed to hold onto a handle with one hand, stand comfortably with feet shoulder-width apart, and face toward the front of the train. While both standing and sitting are common postures on metro trains, the standing posture was chosen because we were not able to consistently find available seats for the experiment. We then assisted them to put on the VR headsets.

Upon the metro train's departure, an experimenter initiated the VR experiment, which is wirelessly casted over Wi-Fi onto the experimenter's phone for real-time monitoring of any issues. During each station-to-station segment, participants experienced three physical acceleration phases. During each phase, a participant experienced two veering paths of two veering rates. Each path spanned 6 seconds, and consists of two 2-second veering experiences. After experiencing two paths, participants verbally conveyed whether the first or second experience was preferred to the experimenter, who then entered it via the buttons on a VR controller for the system to proceed to the next level of the decision tree.

Participants completed 3 metro trip (from Station A to E, E to A, and A to E), each focusing on one of the three veering directions: YAW, PITCH-UP, and PITCH-DOWN in counter-balanced ordering. After each trip, participants removed the VR headsets and exited the train for an 8-minute break, which could be extended as needed, and during which we collected their VR sickness rating and conducted a semi-structured interview. After all trips have been completed, participants ranked their preference among the three veering directions for each of the physical acceleration phases and provided qualitative feedback. The complete study workflow is illustrated as Figure 4.

The study, procedures, and tasks were in compliance with our institution's IRB, ethics, and infection control guidelines. The entire study took about 70 minutes to complete: 10-min introduction + (10 min/trip * 3 trips) + (8 min/break * 3 breaks) + 5-min final interview.

3.3 Participants

We recruited 24 participants (14 females and 10 males), with age ranging from 18~32 (mean=24.0, SD=2.9). For prior VR usage, 19 participants reported less than once per year; 3 reported once per 3 months; 2 reported once per month. For metro usage frequency, 11 participants reported more than once per day, 9 more than once per week, 4 several times per month. Participants' Motion Sickness Susceptibility Questionnaire (MSSQ) scores ranged from 0.0-99.0 on a 0-222 scale [4] (mean=40.9, SD = 27.7), which corresponds to 0-92 percentile of the general population. Participants received a nominal compensation for their participation.

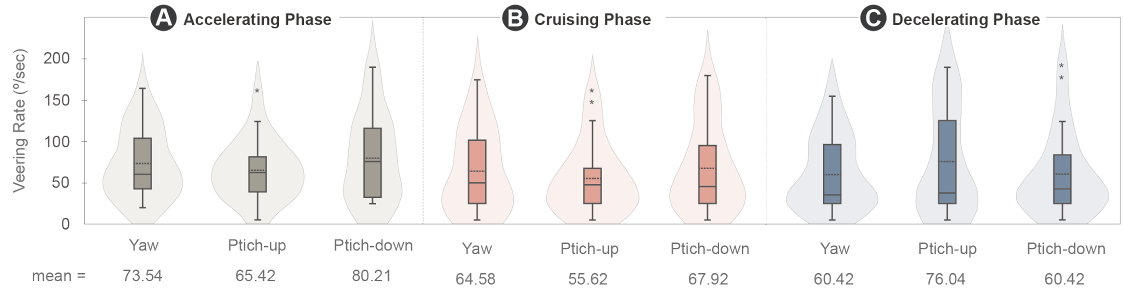

Fig. 6. Participants' most-preferred veering rates for the three acceleration phases: *accelerating*, *cruising*, *decelerating*, and the three veering directions: *yaw*, *pitch-up*, *pitch-down*, shown as violin plots (box plots with the addition of a rotated kernel density plot on each side).

3.4 Results and Discussion

3.4.1 Veering Rate Preference. Participants' most-preferred veering rates are shown in Figure 6 as violin plots, which are box plots with the addition of a rotated kernel density plot on each side.

For the ACCELERATING PHASE, the average veering rates were 73.5, 65.4, and $80.2^{\circ}/sec$ for YAW, PITCH-UP and PITCH-DOWN respectively; 64.6, 55.6, and $67.9^{\circ}/sec$ respectively for the CRUISING PHASE; and 60.4, 76.0, and 60.4 $^{\circ}/sec$ respectively for the DECELERATING PHASE. The most-preferred veering rates overall averaged $67.1^{\circ}/sec$, which is closer to the veering rate of theme park roller coaster designs of up to $90^{\circ}/sec$ [13].

To test for statistical significant differences, we first tested for normality using the Shapiro-Wilk test for normality, which showed a significant departure from normality (p<.05). Therefore, we used Friedman test, which showed no significant difference across these 9 veering rates. We further tested two-tailed Wilcoxon signed-rank test with Bonferroni correction that also showed no statistical significant pair-wise differences.

3.4.2 Veering Direction Preference. Preference ranking for the three veering directions for each acceleration phase is shown in Figure 7. The most preferred veering direction was PITCH UP for the ACCELERATING PHASE at 58.3%, YAW for the CRUISING PHASE at 50.0%, and PITCH DOWN for the DECELERATING PHASE at 54.2% of the participants.

For statistical significance, Friedman tests showed significance only for the ACCELERATING PHASE ($p < .05$). Wilcoxon matched-pairs signed-rank test (two-tailed) with Bonferroni correction showed significant difference with large effect sizes between YAW vs. PITCH UP at the $p < .01$ level ($r > .5$), and with moderate effect sizes between YAW vs. PITCH DOWN at the $p < .1$ level ($r > .3$). The effect size of each pairwise comparison was calculated as $r = Z/\sqrt{n}$ and interpreted using guidelines 0.1 - 0.3 (small), 0.3 0.5 (moderate), and ≥ 0.5 (large effect) [39].

3.4.3 VR Sickness. All participants completed the experiments without early termination. VR sickness was rated on a 10-point FMS scale after each of the three one-way metro trip, and averaged: 1.79 (SD = 1.50), 1.92 (SD = 1.21), and 1.63 (SD = 0.92), respectively.

The highest rating was by P7, who had no prior VR experience and rated an 8 after the first trip. P7 was the only participant that took extra resting time, and subsequent ratings decreased to 4 and 2, and no extra resting time was needed.

The participant with the highest motion sickness susceptibility (MSSQ) at 92%, surprisingly reported nearly no VR sickness with ratings of 2, 1, and 2. P11's most preferred veering rate averaged $33.9^{\circ}/sec$. Although it is much lower than the $67.1^{\circ}/sec$ across all participants, it still corresponds to the 60 Km/hr metro be turning at a radius of 28 meters.

Linear regression of each participant's average veering rate vs. MSSQ score showed $\hat{y} = 0.0417\,X + 65.4$ with a slope coefficient of nearly zero, suggesting that MSSQ scores have little correlation to the most-preferred veering rates.

3.4.4 Qualitative Feedback.

High Veering Rate. In the experiment, participants showed a preference for a relatively high veering rate in the virtual reality (VR) experience, closely mirroring the actual experience of a roller coaster. This preference was particularly evident in scenarios involving significant physical acceleration and deceleration.

P4 articulated a preference for higher veering rates in VR when there was noticeable physical acceleration and deceleration, saying, *"In cases of actual physical acceleration and deceleration, I choose options in VR with a higher veering rate, as it aligns better with my sensations, making VR and physical experiences more congruent."* P20 expressed enjoyment of the combination of physical acceleration with VR, finding it *"faster and more thrilling, without any discomfort."* P8 noted the immersive effect of physical acceleration, mentioning, *"Pairing physical acceleration with VR quickly immerses me in the VR flight (movement) scenario, and deceleration has a similar effect."*

P21 preferred the exhilarating feeling of acceleration and diving, stating, *"I like the thrill of accelerating and diving, it's probably the real acceleration combined with the downward motion, reminding me of a roller coaster ride at an amusement park."* P14 likened the experience to an amusement ride, commenting, *"It feels a lot like being on an amusement park ride. There's a sense of thrill when moving downwards."* P11 observed the role of real-world acceleration in VR, *"Real-world acceleration allows one to feel a pushing force in VR movement, especially during takeoff."* P9 highlighted the realism and excitement of combining physical acceleration with VR pitch-up, *"Physical acceleration paired with a pitch-up in VR, along with the feeling of body movement, is very realistic, giving the thrill of an amusement park ride."*

Physical body posture vs. VR perspective. The alignment of body posture with the virtual reality (VR) experience's visual perspective was a key factor influencing participant preferences during both the accelerating and decelerating phases. In the accelerating phase, participants P1-5, P6-13, P16-17, P19-20, P22-23 preferred the combination of acceleration with a pitch-up motion. They found that the physical sensation of leaning back during acceleration resonated well with the upward visual perspective in VR, as noted by P2 and P5. For instance, P2 remarked, *"The physical sensation aligns more with what's seen on screen, like how your body leans back when a vehicle accelerates."* Conversely, during the decelerating phase, participants P2-6, P8-10, P15, P17-18, P20-21, P23 favored pairing deceleration with a pitch-down motion. The natural forward lean of the body during deceleration matched the downward visual angle, enhancing the experience's realism, as explained by P9. In contrast to these preferences, there was a distinct group of participants who expressed discomfort with certain combinations of movement and visual perspectives. Participants P1, P3-4, P6, P8-9, P17, P19-21, P23 specifically found the pairing of deceleration with a pitch-up motion to be disorienting. They highlighted the inconsistency between body posture and visual perspective during such scenarios. For example, P6 pointed out, *"When turning upwards, you look up, but in a decelerating train, your body leans forward, which doesn't match."* This contrast in preferences highlights the complexity of aligning physical sensations with virtual visuals to create a cohesive and comfortable VR experience.

Everyday motion experiences - airplane takeoff and landing. Participants' preferences during the accelerating and decelerating phases in virtual environments were influenced by their everyday motion experiences, particularly in scenarios like airplane takeoffs and landings. For the accelerating phase paired with a pitch-up motion, participants P1-5, P6-13, P16-17, P19-20, P22-23 found a strong resemblance to real-world experiences such as airplane takeoffs and roller coasters. They felt that the sensation of ascending during acceleration in the virtual setting closely mirrored the

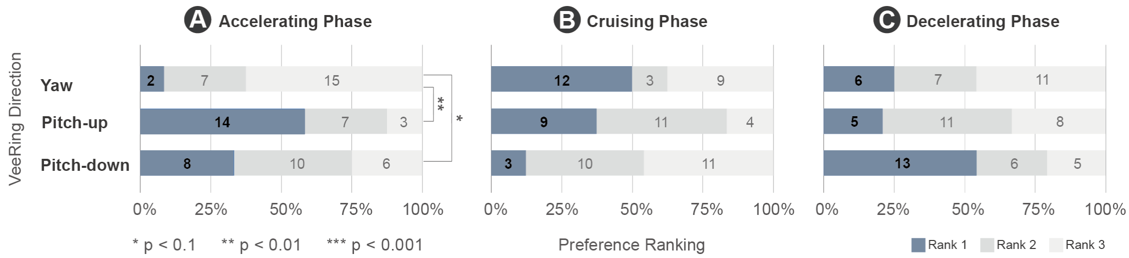

Fig. 7. Formative study participants' preferred veering direction for different physical acceleration phases.

physical experience of an airplane taking off. P1 encapsulated this by saying, *"It feels just like the principle of an airplane ascending, closely matching my usual bodily experiences and expectations,"* indicating the importance of this everyday motion experience in shaping their preference. Similarly, during the decelerating phase paired with a pitch-down motion, participants P2-6, P8-10, P15, P17-18, P20-21, P23 drew parallels to experiences like airplane landings. They noted how the sensation of deceleration in the virtual environment resonated with the feeling of descending in an airplane. As P2 put it, *"Deceleration feels harmonious, as what I see and feel matches, reminiscent of a vehicle or roller coaster descending."* This highlights how everyday experiences of motion, particularly those involving acceleration and deceleration, play a crucial role in determining participant preferences in virtual reality settings.

4 SUMMATIVE USER EXPERIENCE EVALUATION STUDY

Based on the veering preferences from the formative study, we conducted a summative user experience evaluation study for VR motion experiences. Because deviation in VR motion from physical motion introduces sensory conflict [24] that could cause discomfort. The open research question is whether veering enhances the overall experience with comfort taken into account. Our goals are to understand how veering in VR during physical motion affect the user experience, specifically: 1) while experiencing physical motion, how is the experience *with* vs. *without* veering? and 2) how does the presence of mundane, transportation motion affect the experience of veering?

4.1 Study Design

The study used a within-subjects design and was structured as two phases: 1) Phase 1's independent variable was veering, and compared the VR experience during physical motion *with* vs. *without* veering as the two conditions. 2) Phase 2's independent variable was physical motion, and compared the veering experience *with* vs. *without* physical motion as the two conditions.

For both phases, the dependent variables were: 1) 10-point strength-of-preference ratings [8, 10], which are more sensitive to utility differences than independent ratings, for immersion, entertaining, realism, comfort, and overall preference; and 2) 10-point Fast Motion Sickness Scale (FMS).

4.1.1 Physical Motion. For the choice of mundane, everyday physical motion suitable for repeating experiments, we used one of the inter-station segments from the metro route used in the formative study (station D - station E) that had symmetrical accelerating/decelerating phases, suitable for conducting repetitive experiments efficiently. The metro segment has a total duration of 75 seconds, consisting of 19-second accelerating, 37-second cruising, and 19-second decelerating phases.

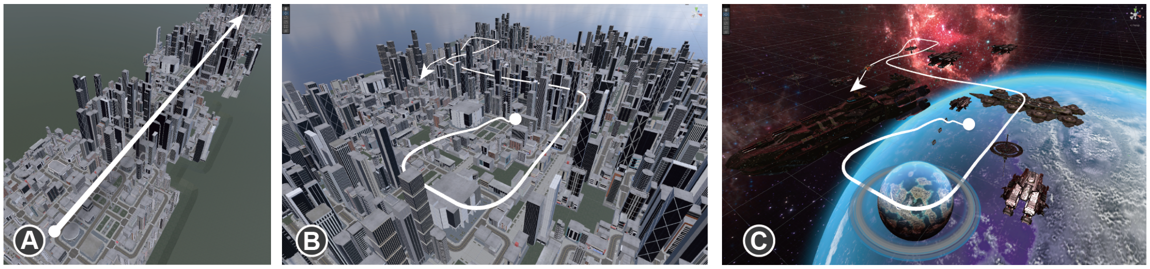

Fig. 8. VR environment and motion paths for the summative study. Phase 1 is in a realistic urban setting and has 2 paths with and without veering: (A) a linear path that matched the physical motion of the metro train; and (B) a motion path with veering, based on the veering preferences from the formative study. (C) Phase 2 is in a inter-planetary scene, using the same veering path design as Phase 1, and passes between spaceships.

4.1.2 VR 360 Motion Experience Design. We developed 2 VR 360 environments for the 2 phases to avoid repeating VR scences, to help keep users more engaged: a city environment for Phase 1 and an inter-planetary environment with spaceships for Phase 2. Phase 1 has 2 motion paths, with and without veering, as shown in Figure 8(a)(b). Phase 2 uses the same path with veering that is placed in a different VR environment, as shown in Figure 8(c).

In order to determine the most-preferred forward speed of the VR experience for the baseline condition of the straight-line VR path without veering, shown in Figure 8(a), we conducted a pilot study with 8 users on metro trains. The most-preferred scaling factor averaged 2.5x, which we applied to all the VR motion experiences in the study to control for the factor. We had tested GPS-based speed sensor and found high error on the metro train with high variance across trips. Therefore we used a simplified linear velocity model of the train using constant acceleration from 0-60 Km/hr during the 19-second accelerating phase and for from 60-0 Km/hr for the decelerating phase, and a constant 60 Km/hr speed was used during the 37-second cruising phase. The same velocity model was used for all conditions.

All paths were designed to be 75 seconds. For designing the path with veering, the veering directions and rates were based on user preferences from the formative study for each of the three acceleration phases, To provide adequate veering experiences and also sufficient stimulation to assess comfort, we designed the path with a total of 13 turns, which is about the same number of turns as a well-known roller coaster ride "Cedar Point Gatekeeper" in the USA that makes 12 turns in 120 seconds [13]. Based on user preference for pitching upward during acceleration and downward during deceleration, and yaw and pitching upward during cruising, we designed 2 pitching-upward during the accelerating phase, 6 yaw and 2 pitching-upward during the 37-second cruising phase, and 3 pitching-downward during the 19-second decelerating phase. To make the paths appear more organic, small random turning of 1-2 degree/sec were added.

4.2 Study Procedure

The study procedure, including safety and VR sickness precautions, were the same as described in the formative study, except for the following:

Participants experienced the two phases in counter-balanced ordering, and the two conditions within each phase were also counter-balanced. For Phase 1, participants would take the metro from Station D - E, then take the return trip from Station E - D. For Phase 2, the stationary condition would be experienced at a predetermined safe standing spot at one of the two stations in the same standing posture as on the metro train. After each phase, participants took

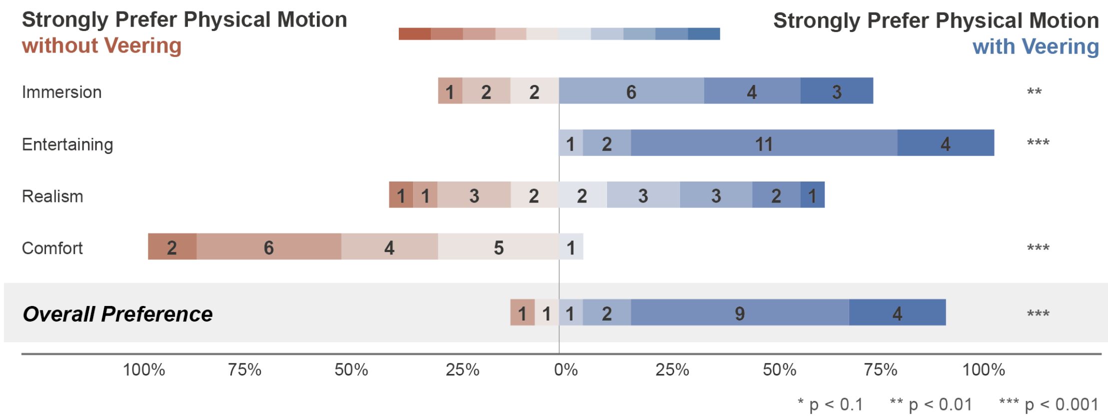

Fig. 9. Preference rating on a 10-point scale while experiencing physical motion *without* vs. *with* veering. Participants preferred veering for Immersion ($p < .01$), Entertaining ($p < .001$), and Realism (67%), and although veering significantly reduced comfort ($p < .001$) as expected due to sensory conflict, participants significantly preferred the overall experience of veering $p < .001$.

a 8-minute break, which could be extended as needed, and during which we collected their VR sickness FMS rating, strength-of-preference ratings between the two conditions, and qualitative feedback.

The entire study took about 45 minutes to complete: 10-min introduction + (10 min/phase * 2 phases) + (8 min/break * 2 breaks)

4.3 Participants

We recruited 18 participants (7 females, 11 males), among which 4 also participated in the formative study with age ranging from 19 to 36 years (mean = 24.7, SD = 4.3).

Their motion sickness susceptibility (MSSQ) scores ranged from 0.0 to 83.2 on a 0-222 scale (mean = 34.7, SD = 24.4), which corresponds to 0-88 percentile of the general population. Regarding VR usage frequency, 12 participants reported less than once per year, 5 once every 3 months, and 1 monthly. For metro usage frequency, 7 participants used the metro several times a day, 5 several times a week, and 6 several times a month. Participants received a nominal compensation for their participation.

4.4 Results and Discussion

All 18 participants completed the experiment without early termination and without taking extra resting time.

4.4.1 Physical Motion with vs. without Veering. Figure 9 shows the 10-point strength-of-preference ratings. Two-tailed, Wilcoxon matched-pairs signed-rank test was used for pair-wise statistical significance. The effect size of each pairwise comparison is calculated as $r=Z/\sqrt{n}$ and interpreted using guidelines 0.1-0.3 (small), 0.3-0.5 (moderate), and ≥ 0.5 (large effect) [39].

All participants preferred veering for ENTERTAINING (100%, $p < .001$, $r > .5$). 72% of participants significantly preferred veering for IMMERSION ($p < .01$, $r > .5$), and 61% preferred it for REALISM, though the difference was not statistically significant. As expected, for COMFORT, participants significantly preferred the experience without veering (94%, $p < .001$, $r > .5$), likely due to sensory conflict. Nevertheless, for OVERALL PREFERENCE which takes comfort into consideration, 89% of participants significantly preferred veering ($p < .001$, $r > .5$) vs. without.

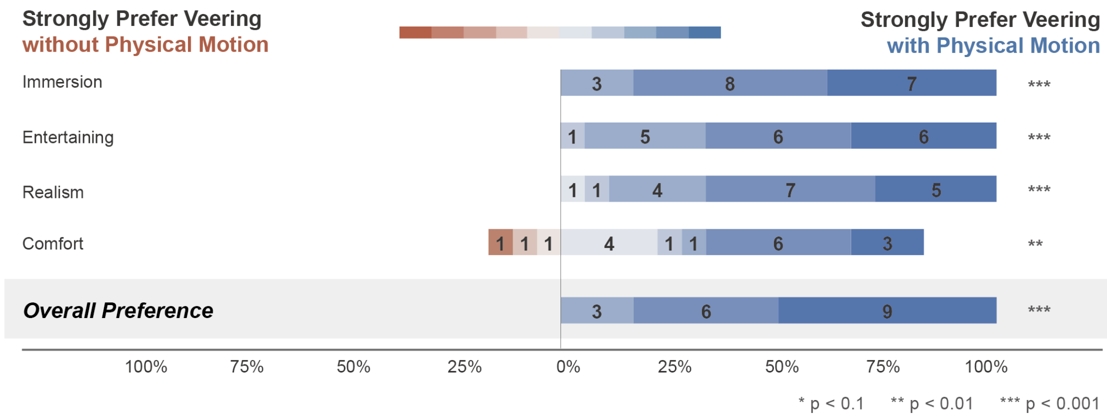

Fig. 10. Preference rating on a 10-point scale for veering *without* vs. *with* mundane, transportation motion. Participants significantly preferred veering for for all aspects, including Immersion, Entertaining, Realism, Comfort, and Overall ($p < .01$-$p < .001$).

4.4.2 Veering with vs. without Mundane, Physical Motion. Figure 10 shows the 10-point strength-of-preference ratings.

All participants significantly preferred the experience with mundane, physical motion for all aspects, including IMMERSION (100%, $p < .001$, $r > .5$), ENTERTAINING ($p < .001$, $r > .5$), REALISM ($p < .001$, $r > .5$), OVERALL PREFERENCE ($p < .001$, $r > .5$) by 100% of participants, and 83% of participants prefer IN-MOTION in the comfort ($p < .01$, $r > .5$) item.

4.4.3 VR Sickness. The 10-point Fast Motion Sickness Scale (FMS) scores ranged between 1-4 and averaged 1.61 (SD = 0.78) after the first phase, and 1.56 (SD = 0.92) after the second phase. No participant requested extra breaks and resting time.

4.4.4 Qualitative Feedback.

WITH VEERING VS. WITHOUT VEERING

Participants liked the new and *"changing scenery"*(P15) that veering provides, and particularly enjoyed the association between acceleration and pitch up and deceleration and pitch down, likening the experience to real-life roller coasters and airplanes: *"with veering, the rise and fall are realistic, resembling a roller coaster with matching body sensations and visual motion."*(P6) and *"veering, especially during landing, is fun and feels like an airplane landing with vibration"*(P11). P6 emphasizes the impact of synchronization, stating, *"With veering, when there is shaking, it feels more like actual driving. The VR turnings are more pronounced, making the pitch up and down feel real."* P18 adds to this, noting, *"With veering, flying up and down aligns well with the body's physically perceived motion, resembling the real experience of taking off and landing."*

In terms of veering direction, participants commented that they preferred pitch up and pitch down more than yaw (P4, P13, P8, P10, P6, P11, and P12). Some reported that veering in yaw sometimes reduced immersion and realism, *"as the car was not turning but the camera was, pulling me out of the VR world."*(P8) and *"moving straight was more realistic than left and right turns, as the latter gives a sensation of being thrown out."*(P13) Some reported discomfort when turning in yaw, but still preferred veering overall (P13, P14, P17).

WITH PHYSICAL MOTION VS. WITHOUT PHYSICAL MOTION

Almost all participants preferred veering with physical motion over veering without it. P8 remarks, *"The comfort and immersion I feel on the vehicle are good. My body feels the movement due to acceleration. This makes me feel that what I* *see matches what my body feels, which I find comfortable."* P5 adds, *"Immersion, entertaining, realism, and comfort are incomparable, far superior to being stationary."*

Most participants mentioned that the vehicle's motion combined with veering significantly improves the experience (P1, P2, P4, P5, P6, P7, P8, P9, P10, P12, P13, P15, P16). P8 comments on the realism added by acceleration and deceleration, *"The entire experience simulates flying very well. I truly felt that I am taking off during acceleration and the landing at deceleratio."* P6 shares a similar experience, *"Matching the visual movement with the motion of the ride feels like being on an actual facility. From takeoff to the gradual acceleration of the subway, it feels like starting a space game, even feeling the body turn with the visuals."*

Participants P3, P11, P13, P15, and P17 mentioned that the car's swaying combined with veering enhances the experience. P17 says, *"Turning left and right while the subway sways really adds to the feeling. The physical movement matches well with the visuals, making it feel like I'm actually flying."*

Regarding the car's sound, participants P1, P3, P5, P9, P11, P12, and P16 found that it also adds to the experience. P16 states, *"Turning upwards is more immersive with the subway's accelerating sound, and downwards with its decelerating sound."* P5 notes, *"The acceleration and deceleration create an effect similar to riding a space shuttle. It's not only the speeding up and slowing down combined with the visuals, but also the sound of the machinery in the subway, which differs from just sitting at a subway station."*

Finally, participants P9 and P16 mentioned that the body's inertial movement combined with veering improves the experience. P16 describes, *"Turning upwards, matched with the subway's acceleration, makes people lean back and look up, and leaning forward when turning downwards with deceleration." P9 finds, "On the car, the experience is more realistic, especially at startup. Leaning back with acceleration and forward with deceleration enhances the realism."*

5 DISCUSSION, LIMITATION, AND FUTURE WORK

5.1 Experience Design

5.1.1 Feasibility of veering techniques. Our study's conclusions indicate that veering techniques are feasible for daily transportation. Moreover, we found that achievable veering rates can be comparable to those of roller coaster rides, reaching up to 60-80 degrees per second, closely resembling the rates observed in roller coaster turning rate studies [13].

Comparing the user's preferred veering direction during various acceleration phases, we identify a strong preference for pitch-up veering during acceleration (58.3% rank 1), pitch-down veering during deceleration(54% rank 1), yaw veering during cruising (50% rank 1). Despite yaw direction veering being favored during cruising in the formative study, participants in the summative study found yaw less appealing. We attribute this difference in user preferences to the increased frequency of veering in the summative study (13 times / 75s) versus the formative study (6 times / 210s). This suggests that veering frequency might influence users' preferred veering directions. Based on this finding, future research can further explore this potential relationship more thoroughly.

5.1.2 Personalized vs General Veering Design. The VR motion experience parameters we identified are designed for general applicability and are suitable for a wide range of users. However, as we observed varied preferred veering rates and directions across users, this suggests the possibility of design based on a personal model. This future exploration could include categorizing users, tailoring experiences, and assessing whether such personalized designs could further improve comfort and enjoyment versus our current findings.

5.2 Example Uses

Based on our user study, we developed four different VR scenes that demonstrate the potential of VeeR, along with extra future use cases that may be applicable. These example uses include 1) fully passive VR experiences, 2) passive VR motions with active tasks, and 3) active VR motion experiences.

Fully passive VR experience. In terms of VR applications, the most straightforward example for implementing VeeR would be the viewing experience for motion simulators, which aligns with our study condition as it doesn't require users' active input. This experience encompasses VR rollercoasters found in theme parks or simulated passenger experiences such as a VR space jet. The system could utilize real-world motion and map them to VR experience based on our study result to provide an improved experience for users.

Passive VR motions with active tasks. On the other hand, while games that involve active tasks drawing attention away from the background motion experience may not align with our study condition, active tasks that highlight the use of its passive motion experience is well-suited for applying VeeR. An example of such games is endless runners (*e.g.* VR subway Sprinters [12] and Temple Run VR [45]), where players must time their actions based on the relative speed and movement of themselves and the obstacles or surroundings. For example, in the City Runner and Music Runner VR games we built (shown as Figure 11 (A) and (B)), players experience Veering motion experience alongside the avatar but must time their active inputs to dodge or score during movement.

Another relevant game genre is rail shooters, similar to titles like Epic Roller Coasters [11] and Pokemon Snap [33], where players continuously experience a passive virtual motion but aim at targets based on their position and movement. For example, in the space shooter and snapshooter games we developed, as shown in Figure 11 (C) and (D), players must factor in the veering motion to attack or capture images at the correct angle and timing.

Active VR motions experiences. Although deviating from our study's design, our current results suggest a modulable range of veering rates for participants, opening up possibilities for user-controlled veering motion during gameplay. This could enable motion games with full active control, like flight simulators or VR car racing. We are currently exploring this potential future direction, including both required system capabilities and user experience limitations.

5.3 Limitation

5.3.1 Additional Vehicle and Transportation. In terms of daily motion direction, although our study utilizes a metro rail as our primary apparatus due to its controlled duration of acceleration and deceleration, our findings should be applicable to longer rides, such as those experienced on trains or in cars that feature similar speed ranges.

5.3.2 User posture and interaction. As the first work to investigate the feasibility of using veering for mundane, everyday motion, we focused on designing a passive VR viewing experience using a common posture, which is a forward-facing, standing posture on the metro while holding on to a pole. There are several other common postures, such as sitting and standing while facing forward and sideways, as depicted in Fig. 12. We are exploring VR motion experience designs and interactive input methods using user postures, such as a skateboarding experience while standing sideways or using the grab handle to control a hang glider. Additionally, user orientation, e.g. forward vs. sideways, may be the preferred veering, and further investigation is needed for other orientations.

5.3.3 Types of motion. Our study results showed that even the highly mundane motions of a metro moving in a straight route can be designed into entertaining VR motion experiences similar to roller coasters, significantly expanding the

Fig. 11. Images illustrating how we can utilize mundane physical motion to design VR experiences. Using Unity, we created four distinct game scenarios, highlighting potential applications in motion games such as Endless Runner and Rail Shooter. In VR, users continuously move along a predefined path and can engage in active tasks

types of motion that VR designers can apply veering techniques to. Beyond the straight-line motion that we investigated, there are multitudes of everyday motions, such as turning left/right or up/down and changing in acceleration (jerk), that offer more opportunities to apply veering to. Furthermore, different transportation vehicles, e.g. cars, trains, airplanes and ships, may have distinctive motion, vibration and noise patterns that can be investigated further to better match the motion experiences in VR.

5.4 Safety and Awareness

Our studies demonstrated the feasibility of turning mundane transportation experiences into entertaining VR rides, with participants from the study wanting to use it during their own daily commute (P4, P5) and reporting that *"The very moment of ascending acceleration makes me feel truly immersed in another VR world. The sense of immersion is powerful. It's a unique VR experience that I'd want to relive."* [P5]

Nevertheless, there remain significant safety barriers for VR and MR usage for everyday transportation beyond safer settings such as private cars, airplanes and metros in cities such as X city and Y city that must be addressed prior to broader usage. We are exploring MR experience designs that sense and reveal the surroundings to provide better awareness as needed, such as when arriving at a metro stop when people prepare to board and disembark, using concepts similar to the physical dial on the Apple Vision Pro that seamlessly transitions between VR and reality.

6 CONCLUSION

We have validated the feasibility of applying veering techniques to mundane everyday motion to significantly enhance the overall user experience even with comfort taken into consideration. Through a series of formative, perceptual, and user experience studies with a combined total of 42 participants, results showed the feasibility of creating entertaining VR motion experiences with veering rates, significantly expanding the flexibility for VR designers to create immersive and entertaining VR motion experiences for everyday motion.

Our work aims to explore the feasibility of deliberately designing VR motion that diverges from users' physical movements, transforming mundane, everyday transportation motion into more entertaining VR experiences. This contrasts with prior works that precisely synchronize VR motion to physical movement. Through in-situ perceptual studies, we identified user-preferred veering rates and directions during each acceleration phase and validated through a user experience evaluation study that utilizing deviations between physical and VR motions is feasible and effective. This opens up discussions on the potential for experience design.

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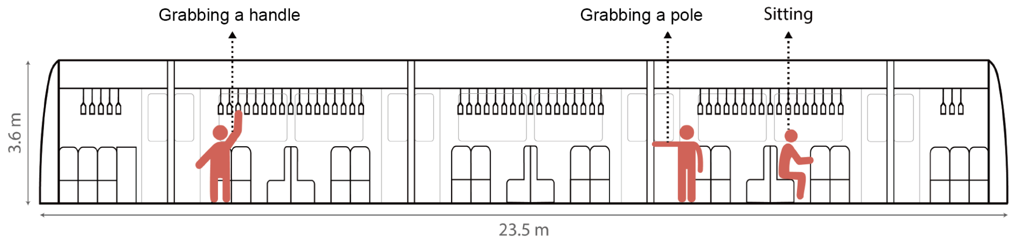

Fig. 12. Common user postures, orientations, and hold points on a metro train.

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